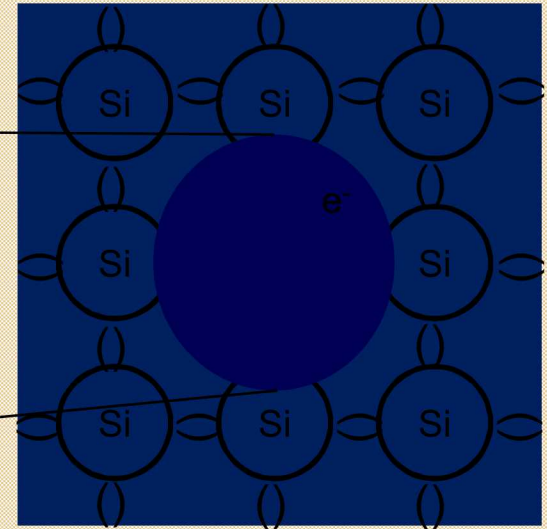
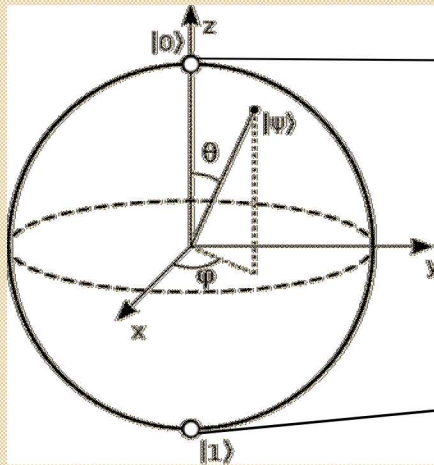




Counted Antimony donors in Silicon quantum dots



M. Singh, J. L. Pacheco, D. Perry, E. Garratt, G. Ten Eyck, N. C. Bishop, J. R. Wendt, D. R. Luhman, E. Bielejec, M. S. Carroll and M. P. Lilly

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE Office of Basic Energy Sciences user facility. The work was supported by Sandia National Laboratories Directed Research and Development Program. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.



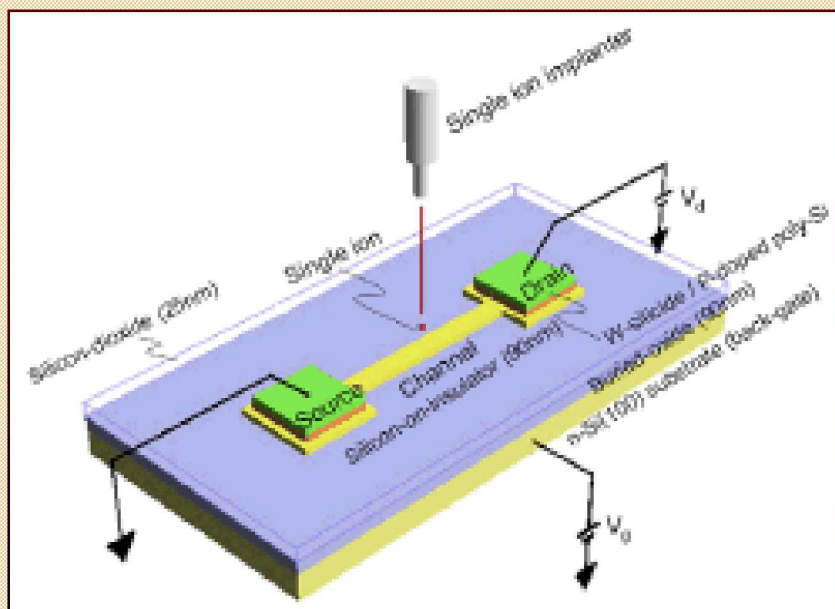
Why count donors?

Two qubit experiments require deterministic control over number of donors

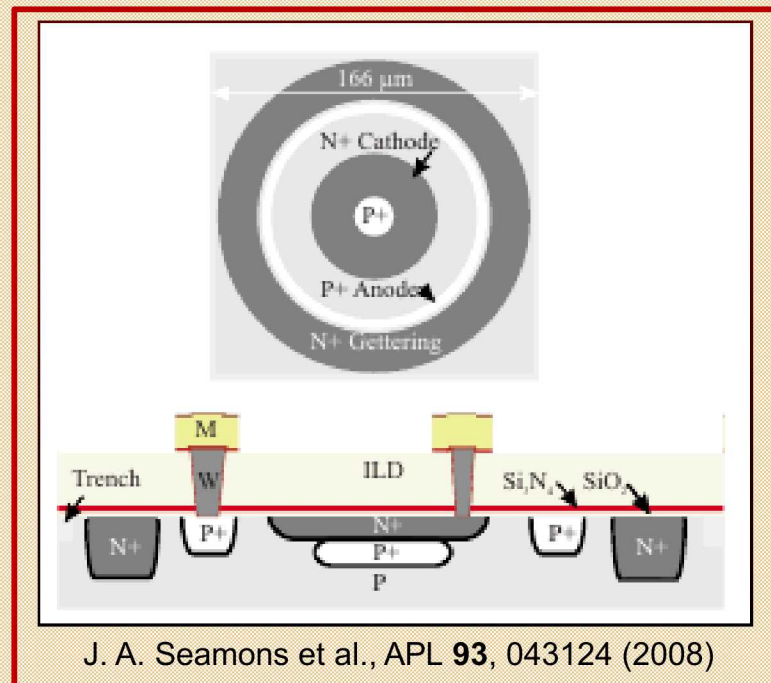


B.E. Kane, Nature **393**, 133 (1998)

How to count donors:

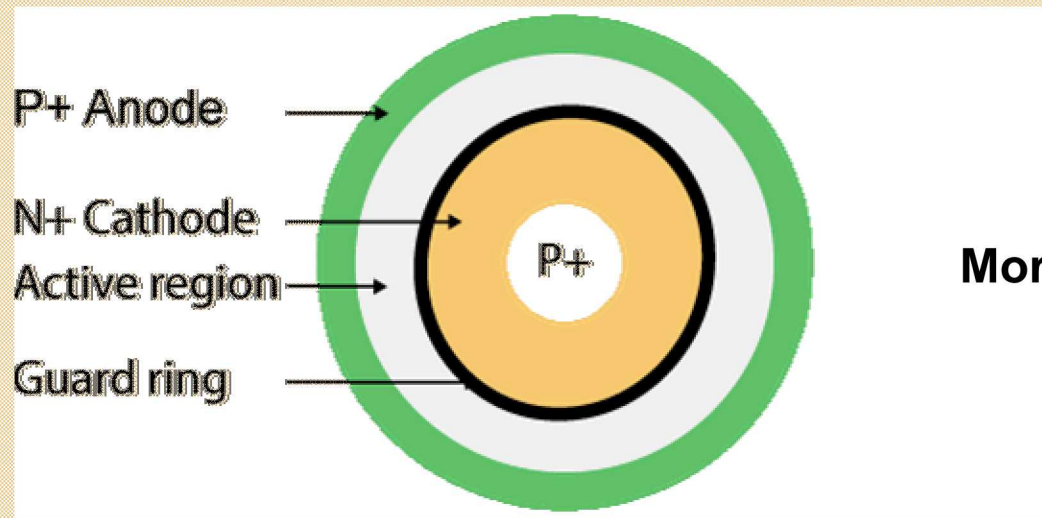


T. Shinada et al., Nanotechnology **19**, 345202 (2008)

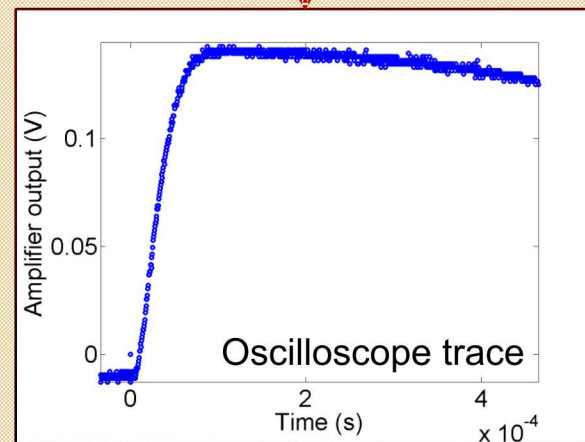
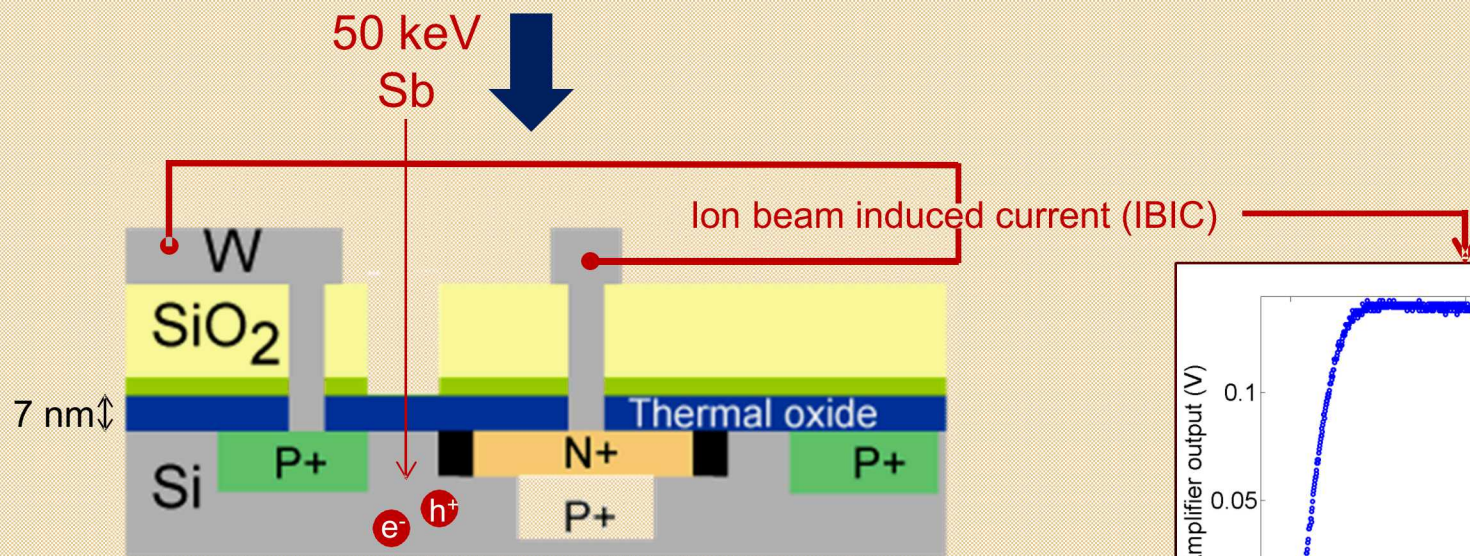


J. A. Seamons et al., APL **93**, 043124 (2008)

How the diode detector works



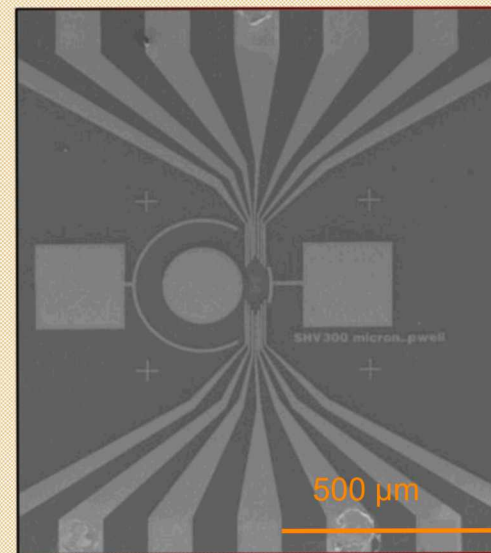
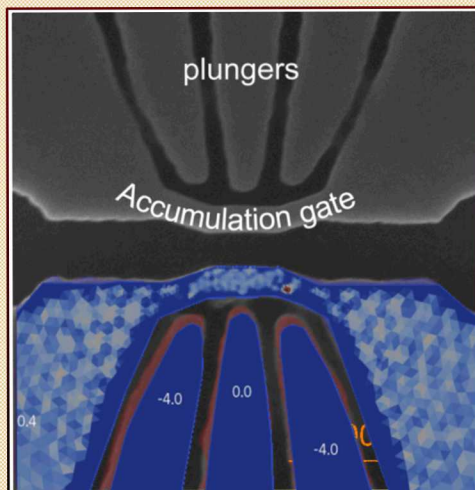
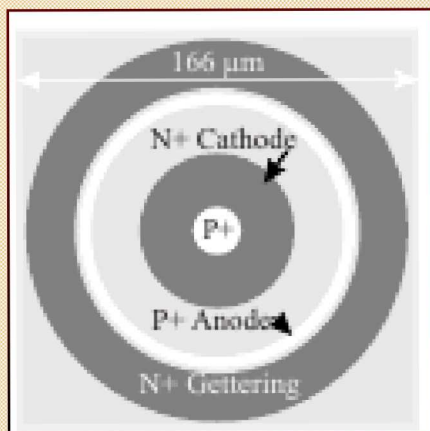
More details: J. Pacheco – S37.00010





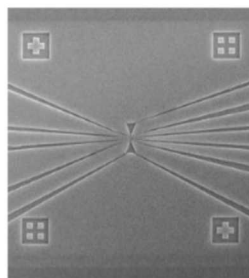
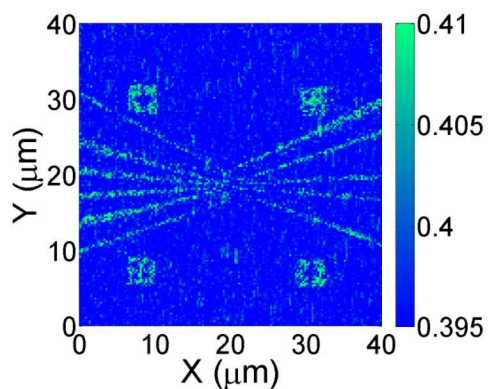
Integration with Single Electron Transistors

Two qubit experiments also require functional SETs



Integration with Single Electron Transistors

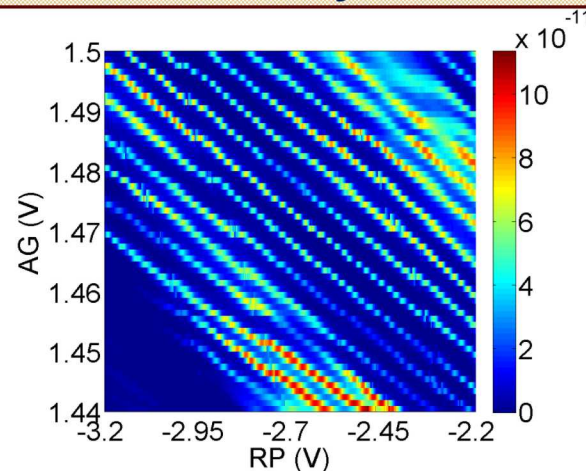
Single ion detection



25 μm

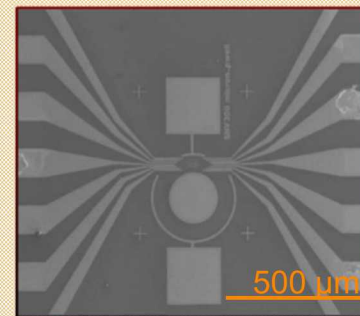
Ion beam induced current map with 50 keV Sb $\langle 1 \rangle$ ion/pulse
and SEM image of device

**SET with capacitances agree
with simulations of an
electrostatically defined dot**

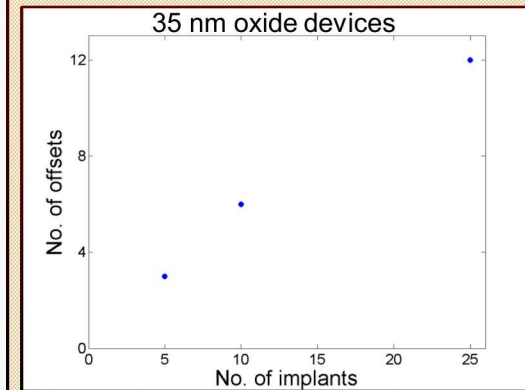
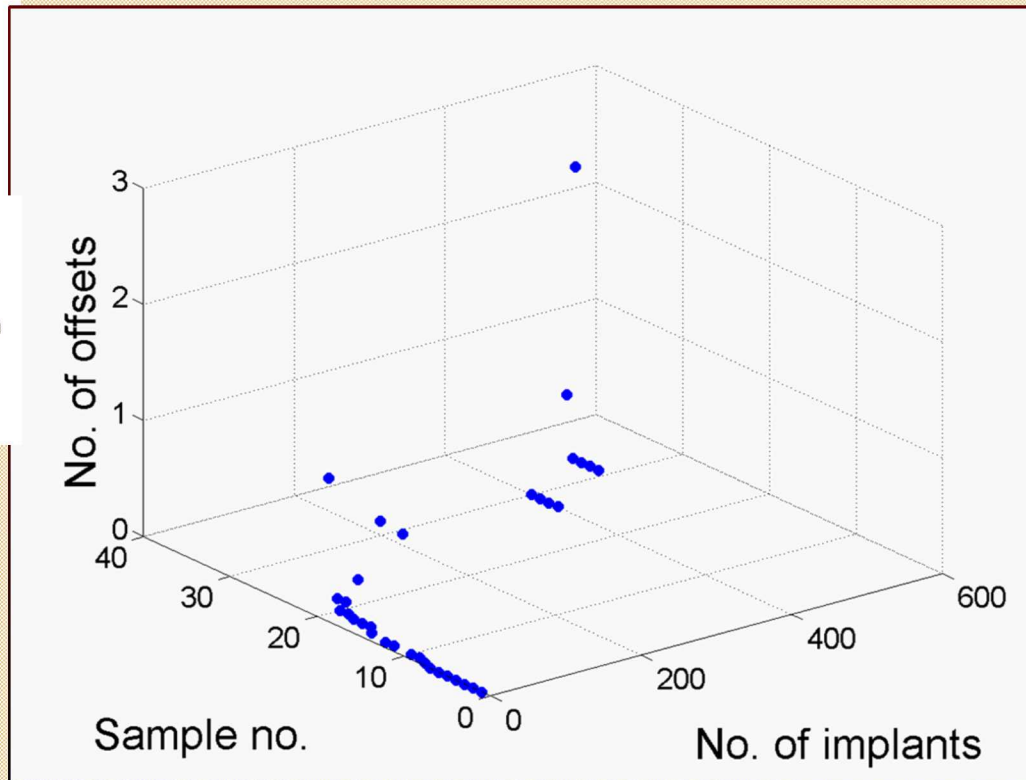
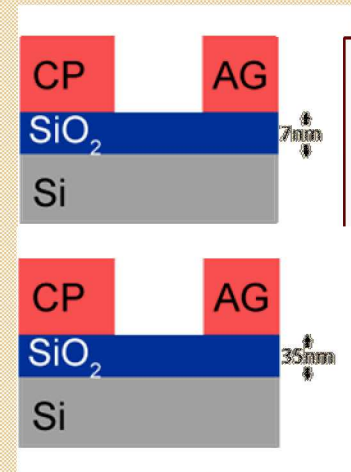


$T = 25 \text{ mK}$, $C_{AG} = 26.7 \text{ aF}$, $C_{RP} = 1.6 \text{ aF}$, C_{CP}
 $= 2.2 \text{ aF}$, $C_{LP} = 1.4 \text{ aF}$

Diode detectors that can detect a single ion
integrated with functional SETs.



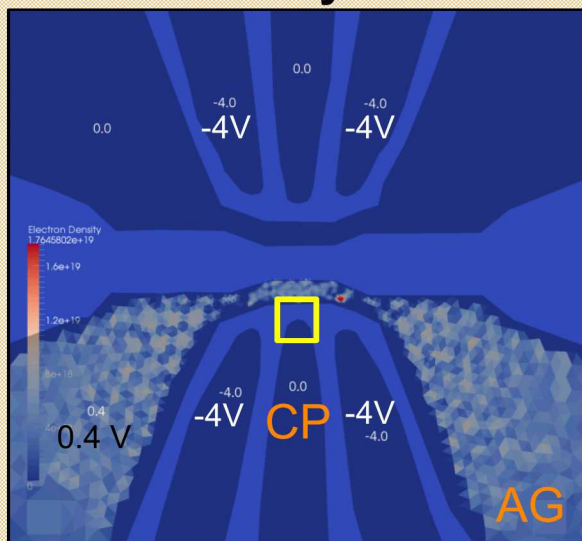
Offsets in 7 nm devices



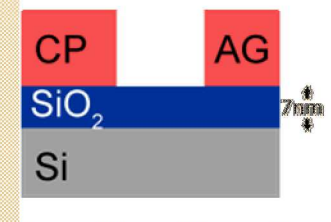
- Number of offsets always very small compared to the of number of implants
- Ruled out possibilities of being at the wrong depth, wrong location, donors not activated etc.
- Exploring geometry considerations with semi-classical simulations

Insight from simulations – 7 nm oxide

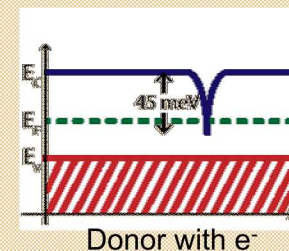
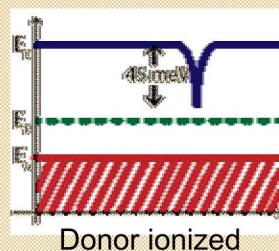
Electron density at interface



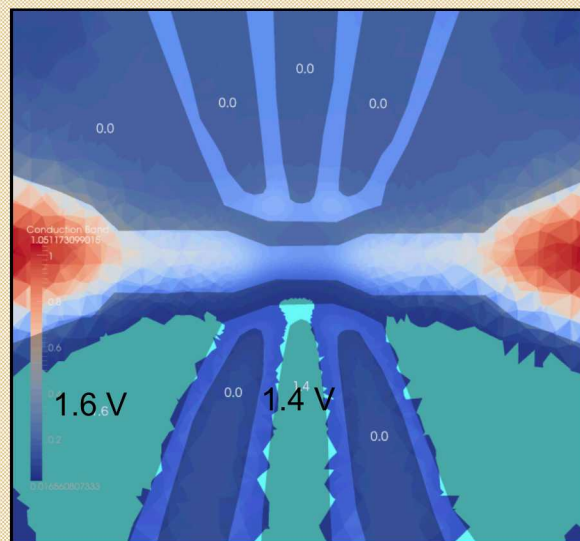
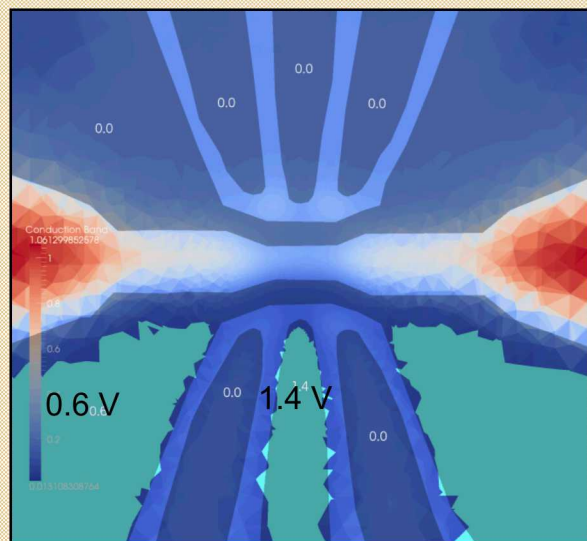
- Threshold of ~ 0.4 V obtained using fixed charge as a free parameter



- Plungers have 'weak' effect compared to AG



Conduction band 30 nm below Si/SiO₂ interface.

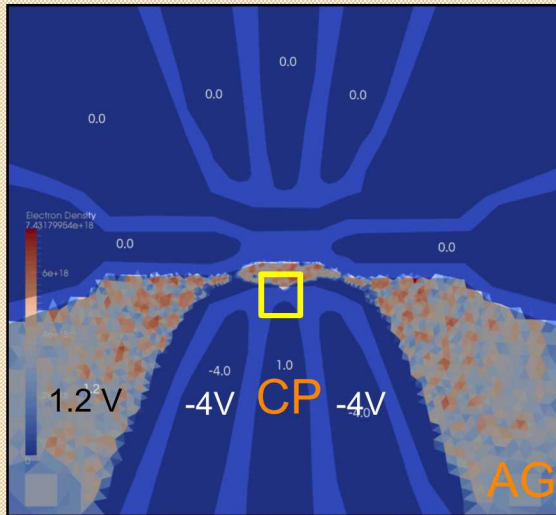


- To change ionization state of donor, AG $\sim 4V_{th}$ - making dot formation impossible

Offsets in 7nm oxide samples are difficult to observe

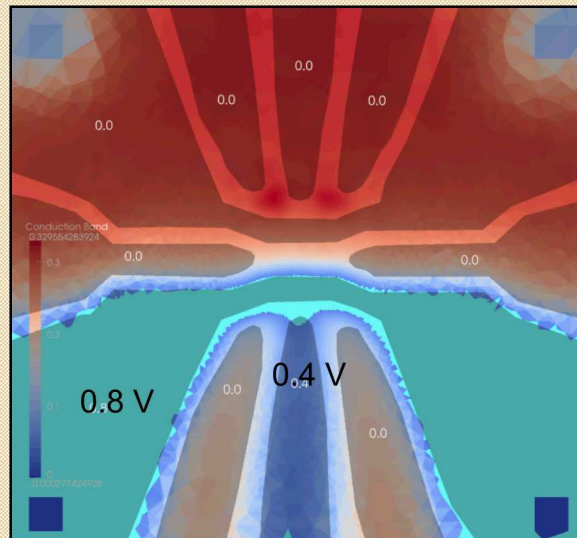
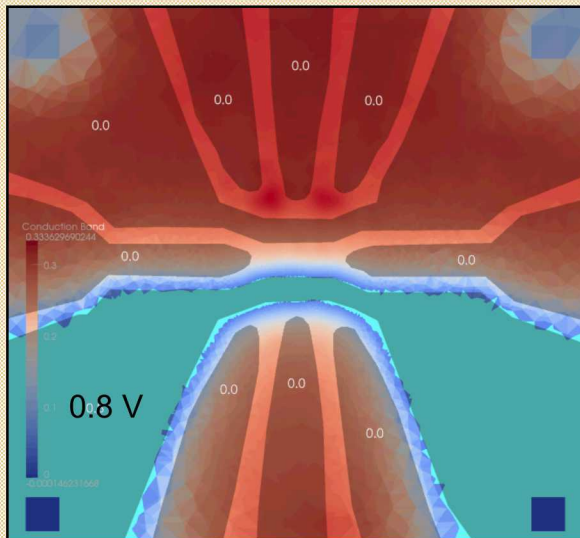
Insight from simulations – 35 nm oxide

Electron density at interface



- Threshold of ~ 0.8 V obtained using fixed charge as a free parameter
- Plungers have stronger coupling than the 7 nm case

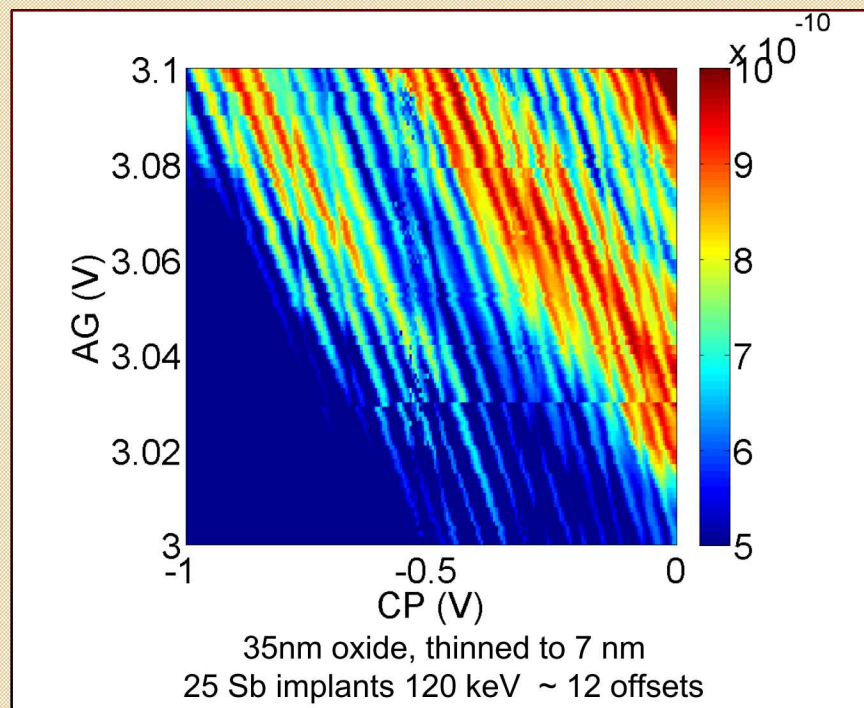
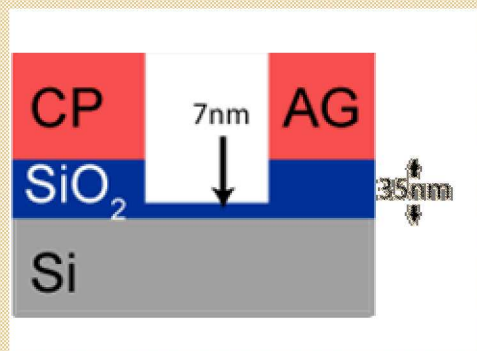
Conduction band 30 nm below Si/SiO₂ interface. Donors in green regions have e⁻



- To change ionization state of donor, a small change on CP is sufficient

Offsets in 35nm
oxide samples are
easy to observe

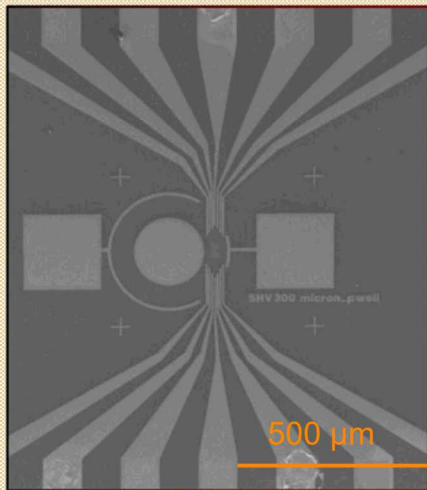
Experimental test



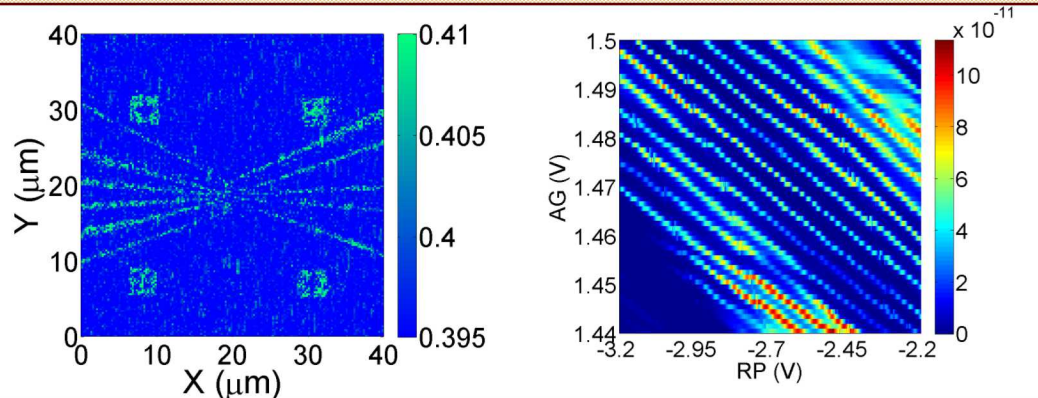
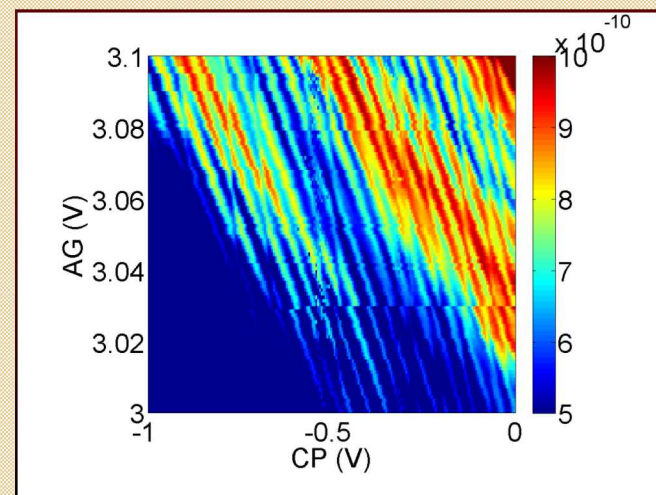
- In samples with 50 timed implants ~ 20 offsets are seen, with 10 implants ~ 6 offsets and with 5 implants ~ 2 offsets are seen
- The geometrical problem indicated by QCAD is the most likely reason for the missing offsets
- New devices with optimal geometry taken into consideration have been fabricated

Results

1. Samples with functional SETs integrated with single ion detectors are fabricated



2. Functional geometry for observing offsets is predicted and tested

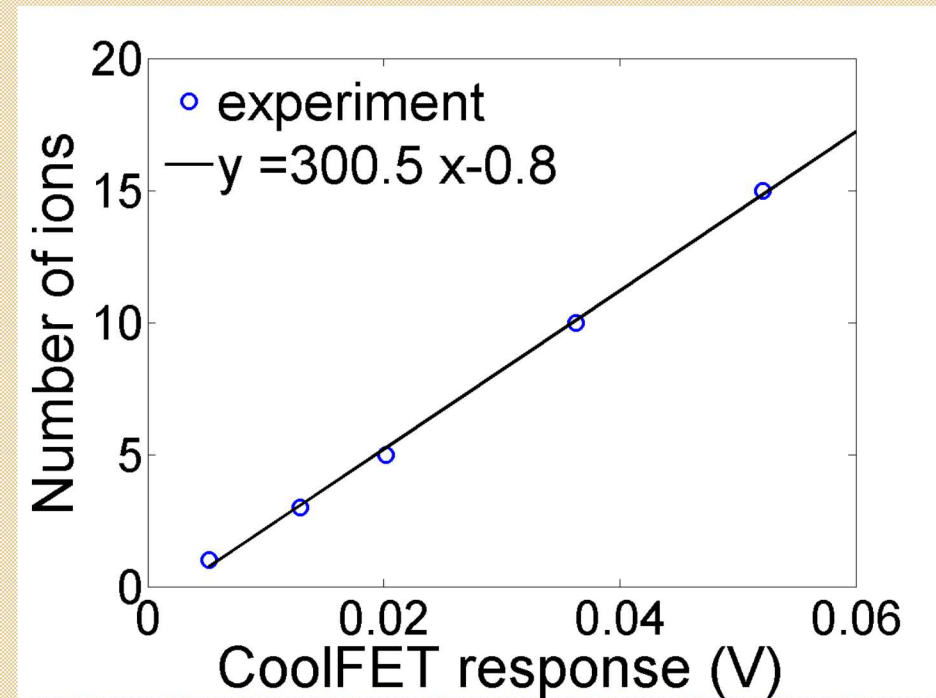
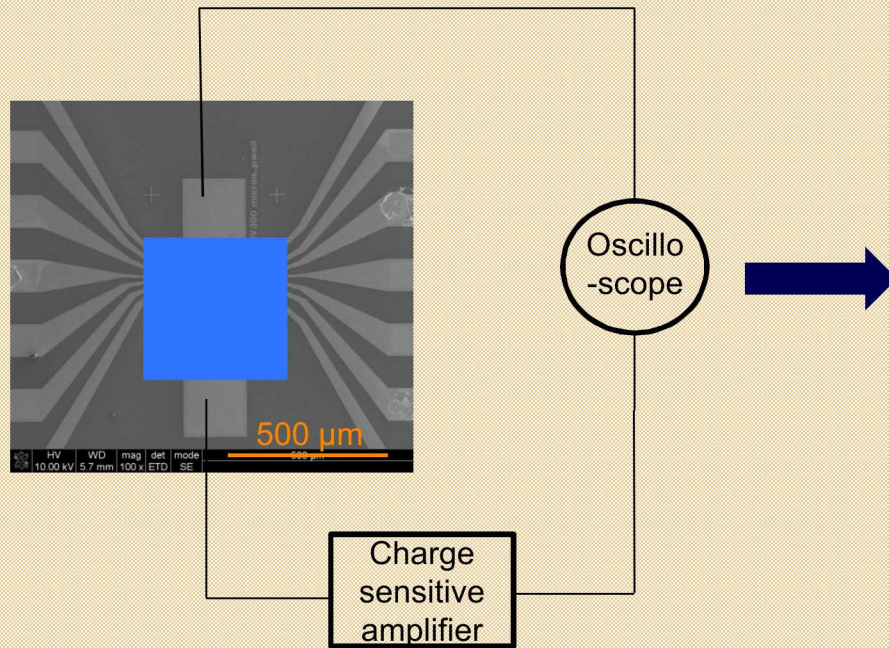


Thank you

Additional Information

Calibration and counting

Counting the ion implants



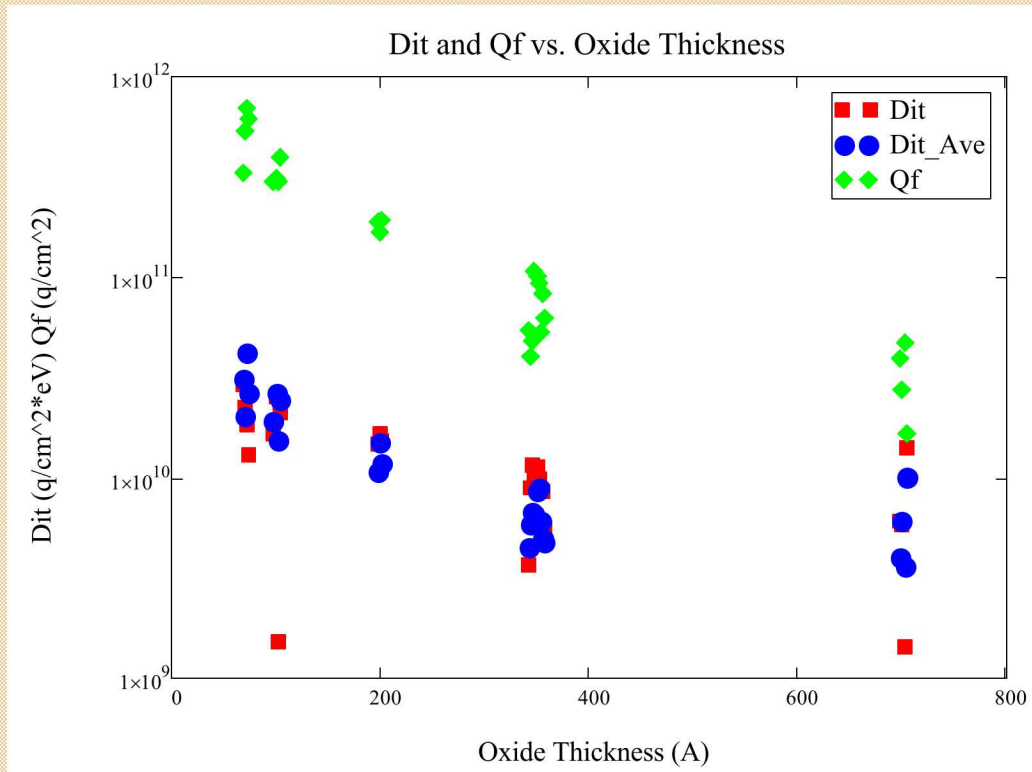
- With this detection capability, the number of ions being implanted can be counted

Sample Synthesis: 7 nm oxide

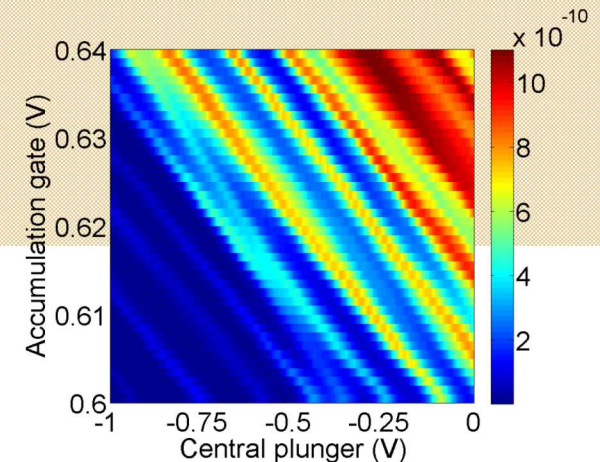
1. Interface trapped charge (D_{it}) and fixed charge (Q_f) are concerns for dots and donors near the SiO_2/Si interface
2. Thinner oxides lead to higher fixed charge

We require deterministic control over:

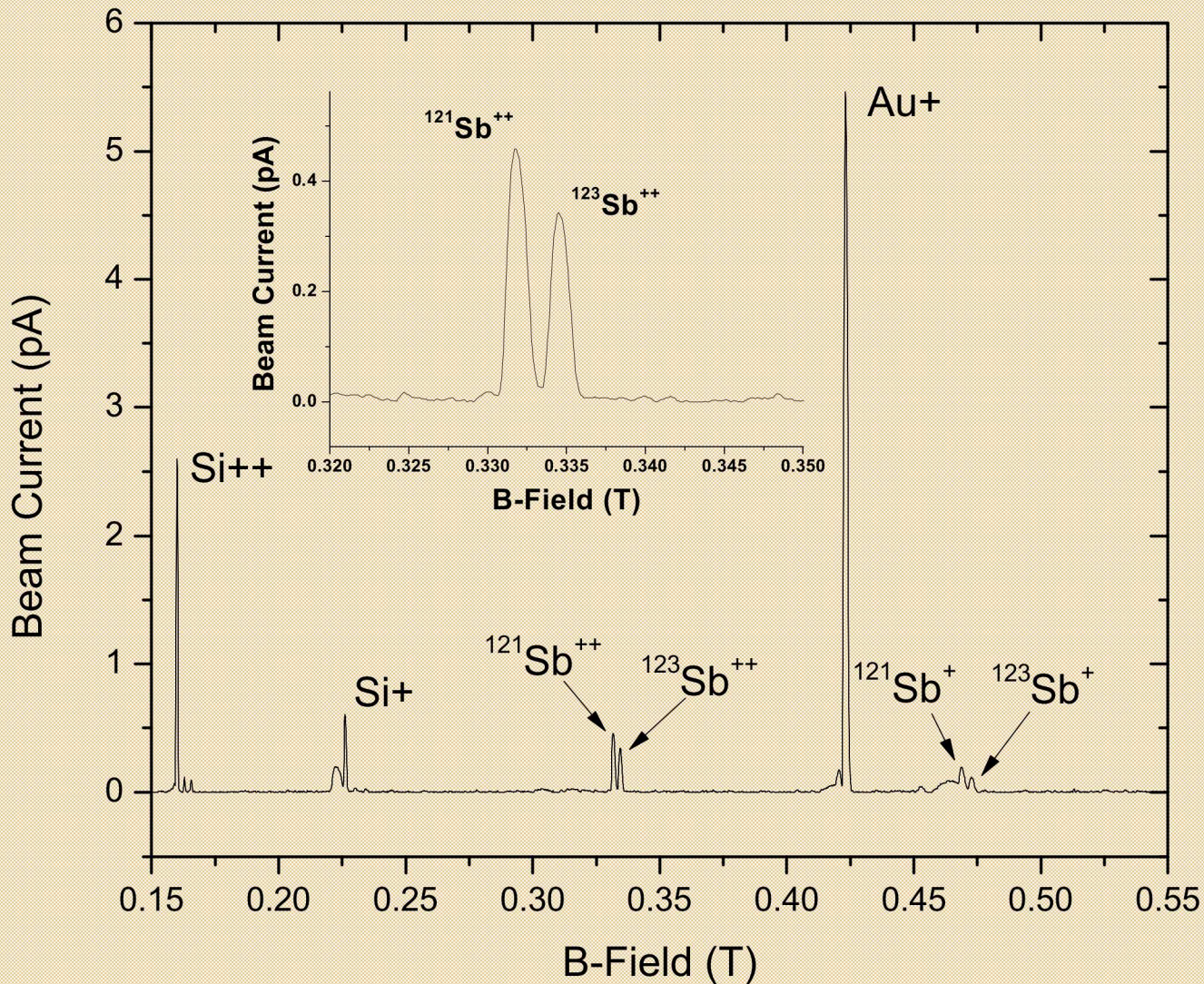
1. Placement of donors: needs thin oxide
2. Number of donors



However, we are able to obtain stable single dots in these systems



AuSiSb Mass Spectrum



hydrogen 1 H 1.0079																		helium 2 He 4.0026																	
lithium 3 Li 6.941		beryllium 4 Be 9.0122																		boron 5 B 10.811		carbon 6 C 12.011		nitrogen 7 N 14.007		oxygen 8 O 15.999		fluorine 9 F 18.998		neon 10 Ne 20.180					
																								phosphorus 15 P 30.974		sulfur 16 S 32.065		chlorine 17 Cl 35.453		argon 18 Ar 39.948					
potassium 19 K 39.098		calcium 20 Ca 40.078		scandium 21 Sc 44.956		titanium 22 Ti 47.867		vanadium 23 V 50.942		chromium 24 Cr 51.996		manganese 25 Mn 54.938		iron 26 Fe 55.845		cobalt 27 Co 58.933		nickel 28 Ni 58.693		copper 29 Cu 63.546		zinc 30 Zn 65.39						selenium 34 Se 78.96		bromine 35 Br 79.904		krypton 36 Kr 83.80			
rubidium 37 Rb 85.468		strontium 38 Sr 87.62		yttrium 39 Y 88.906																										tellurium 52 Te 127.60		iodine 53 I 126.90		xenon 54 Xe 131.29	
caesium 55 Cs 132.91		barium 56 Ba 137.33		57-70 ✱		lutetium 71 Lu 174.97		hafnium 72 Hf 178.49		tantalum 73 Ta 180.95		tungsten 74 W 183.84		rhenium 75 Re 186.21		osmium 76 Os 190.23		iridium 77 Ir 192.22				mercury 80 Hg 200.59						polonium 84 Po [209]		astatine 85 At [210]		radon 86 Rn [222]			
francium 87 Fr [223]		radium 88 Ra [226]		89-102 ✱ ✱		lawrencium 103 Lr [262]		rutherfordium 104 Rf [261]		dubnium 105 Db [262]		seaborgium 106 Sg [266]		bohrium 107 Bh [264]		hassium 108 Hs [269]		meitnerium 109 Mt [268]				ununbium 112 Uub [277]													
																						ununquadium 114 Uuq [289]													



0.5 μm

* Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
** Actinide series					neptunium 93 Np [237]									nobelium 102 No [259]

Capable of Generating Ion Beams from ~1/3 of the Periodic Table